Seismic structural design optimisation

BEDRAOUI Ichraq

Under the supervision of Mrs EL MKHALET Mouna

PLAN

1 Introduction

2 Choice justification

3 Generalities

- A general idea on how earthquakes affect buildings
- How to build an earthquake proof building

4 Optimisation Method:

- Eigenfrequency Optimization Method
- Challenges that face this method
- Solution
- Advantages of the method
- Case study and results
- conclusion

5 Subject expansion

- Moroccan statistics and new projects in the design office
- Conclusion and references

Introduction:

Of all the species that inhabited the earth, humans shined with their uniqueness and their ability to combine and gather knowledge from their surroundings in order to lead a better life. Shelter or as we call it in the modern era “a building/a house”, was a necessity for the survival of our species. We needed a way to protect ourselves from the most destructive forces on earth, earthquakes, volcanos, tornados and many more. It was a hard task but throughout history, we made an impressive progress in building breath taking structures that withstand even the harshest climates.

Structural design has always been a very interesting and creative segment in a large variety of engineering projects. Structures of course should be built in a way to resist applied forces stress and constraints and do not exceed certain deformations, in order to ensure safety. Moreover, structures should be economical. So certainly, the best designs are the ones that satisfy stress and displacement constraints and result in the least cost of construction. However, it’s theoretical, and such designs only appear to exist on paper because we need to consider other factors. Consequently, our goal became the optimization of the weight, and the cost of structures while simultaneously maintaining safety when facing unpredictable factors such as natural disasters.

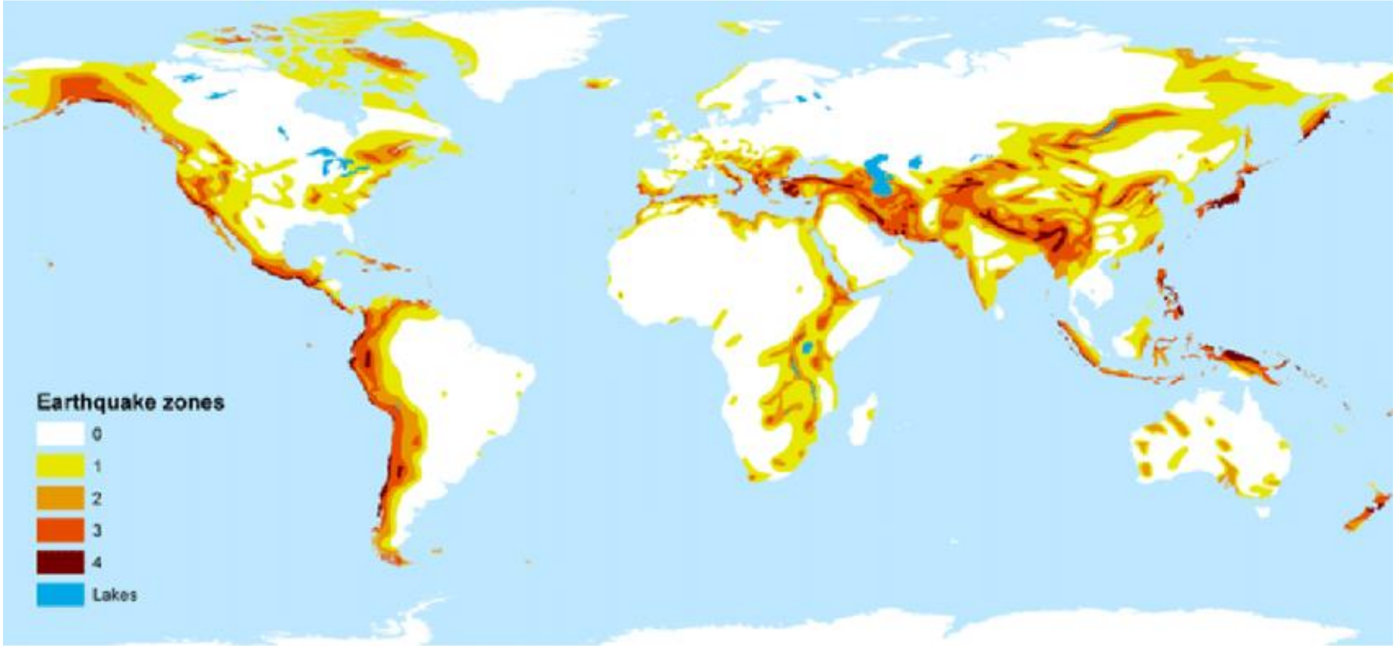
Now if we dive deep in the nature of these forces, we find that they are dynamic with a magnitude that varies in time. Therefore, a dynamic analysis requires large amounts of data interpretation and information processing, resulting in a costly structure design. In a competitive world, optimum design has a great importance in an economic design of structures.

*An optimizer is a formal plan or an algorithm, used to search for a “best” design that satisfies all conditions.

Choice justification:

According to the national earthquake centre, there's an average of 20000 earthquakes yearly around the globe or approximately 55 earthquakes per day with 16 major earthquakes in the magnitude 7 range or greater. And since they are unpredictable, they can cause serious damage out of nowhere. Now this damage isn't caused by the quake itself but by the collapse of buildings with people inside them which is followed with deadly secondary effects and catastrophic aftershocks. Hence, earthquake proof buildings are a must, especially when no particular zone is safe from this natural occurrence. Seismic structural designs are based on a variety of interesting ideas that not only could save lives but also cut down on the costs of damaged buildings.

The following picture is a map indicating earthquake zones with their intensity ranging from the least to most dangerous zones.



A general idea on how earthquakes affect buildings:

Before we start optimising our designs, it is important that we first understand how earthquakes affect man-made structures. When an earthquake occurs, it sends shockwaves all throughout the ground, in all directions and within small intervals. Most buildings are generally made to resist vertical forces such as gravity and their weight, however they are poorly designed when it comes to side-to-side forces causing an almost immediate collapse to the structure when hit by strong seismic waves. Now you might be thinking that a skyscraper is more prone to collapsing, but it isn't the case as tall buildings are more flexible and therefore can bounce back easier.

When the ground shakes, buildings respond to the accelerations transmitted from the ground through the structure's foundation. The inertia of the building (it wants to stay at rest) can cause shearing of the structure which can concentrate stresses on the weak walls or joints in the structure resulting in failure or perhaps total collapse. The type of shaking and the frequency of shaking depends on the structure.

How to build an earthquake proof building:

Little story:

When the shaking started at 5:46 a.m., Yasuhisa Itakura, an architect at a big Japanese construction company in Kobe, was sitting at his desk finishing a report he had toiled over all night. His office swayed, but the books stayed on their shelves and nothing fell off his desk.

“I thought to myself, this earthquake is not that big,” Mr. Itakura said.

It was, in fact, catastrophic. The Great Hanshin earthquake of January 17, 1995, killed more than 6,000 people in and around the industrial port city.

Mr. Itakura had been cushioned from the violence of the earthquake because his three-story office building was sitting on an experimental foundation made from rubber — an early version of an engineering technique called base isolation.

The technique that protected Mr. Itakura’s building is used in roughly 9,000 structures in Japan today, up from just two dozen at the time of the Kobe earthquake. Thousands of other buildings in the country have been fitted with shock-absorbing devices that can greatly reduce damage and prevent collapse.

Chile, China, Italy, Mexico, Peru, Turkey and other countries vulnerable to earthquakes have adopted the technologies to varying degrees. But with notable exceptions, including Apple’s new headquarters in Silicon Valley, the innovations have been used only sparingly in the United States. Seismic safety advocates describe this as a missed opportunity to save billions of dollars in reconstruction costs after the inevitable Big One strikes.

To make a building more resistant to earthquakes, there are many methods:

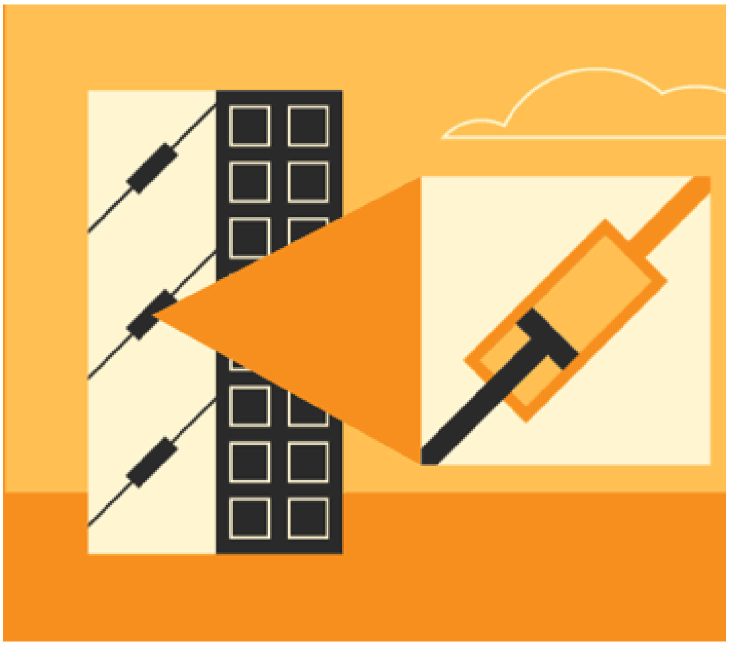
1. Create a Flexible Foundation

One way to resist ground forces is to “lift” the building’s foundation above the earth. Base isolation involves constructing a building on top of flexible pads made of steel, rubber, and lead. When the base moves during the earthquake, the isolators vibrate while the structure itself remains steady. This effectively helps to absorb seismic waves and prevent them from traveling through a building,

2. Counter Forces with Damping

You might be aware that cars have shock absorbers. However, you might not know that engineers also use them for making earthquake-resistant buildings. Similar to their use in cars, shock absorbers reduce the magnitude of shockwaves and help buildings slow down. This is accomplished in two ways: vibrational control devices and pendulum dampers.

The effect of viscous damping and yielding, on the reduction of the seismic responses of steel buildings modelled as three-dimensional (3D) complex multidegree of freedom (MDOF) systems, is studied. The reduction produced by damping may be larger or smaller than that of yielding. This reduction can significantly vary from one structural idealization to another and is smaller for global than for local response parameters, which in turn depends on the particular local response parameter.



The uncertainty in the estimation is significantly larger for local response parameter and decreases as damping increases. The results show the limitations of the commonly used static equivalent lateral force procedure where local and global response parameters are reduced in the same proportion. It is concluded that estimating the effect of damping and yielding on the seismic response of steel buildings by using simplified models may be a very crude approximation. Moreover, the effect of yielding should be explicitly calculated by using complex 3D MDOF models instead of estimating it in terms of equivalent viscous damping. The findings of this paper are for the particular models used in the study. Much more research is needed to reach more general conclusions.

3-Reinforce the Building's Structure:

To withstand collapse, buildings need to redistribute the forces that travel through them during a seismic event. Shear walls, cross braces, diaphragms, and moment-resisting frames are central to reinforcing a building.

Shear walls are a useful building technology that helps to transfer earthquake forces. Made of panels, these walls help a building keep its shape during movement. Shear walls are often supported by diagonal cross braces. These steel beams have the ability to support compression and tension, which helps to counteract the pressure and push forces back to the foundation.

Diaphragms are a central part of a building's structure. Consisting of the floors of the building, the roof, and the decks placed over them, diaphragms help remove tension from the floor and push force to the vertical structures of the building. Moment-resisting frames provide more flexibility in a building's design. This structure is placed among the joints of the building and allows for the columns and beams to bend while the joints remain rigid. Thus, the building is able to resist the larger forces of an earthquake while allowing designers more freedom to arrange building elements.

In the following paragraphs, I'm going to explain the optimization method used for "reinforcing the building's structure".

Definition:

Steel Moment Frame Design:

Steel moment framework uses a series of columns and beams, where the attachments are formed using a combination of welding and bolting. These connections are called "moment connections", with no releases to the joint when it is structurally analysed. The various connection methods used to achieve these connections have evolved throughout the decades, but as welding techniques and bolt strength have improved, the welded flange connection became the moment frame joint connection of choice.

Optimisation Method:

Eigenfrequency Optimization Method for the Design of Steel Moment Resisting Frames

Eigenfrequency optimization describes a problem where one or more natural frequencies, of a structure or mechanism are optimized. This approach makes sense when the structures are subjected to dynamic loads whose response depends on one or more of its natural frequencies. Several problems involving dynamic loads in structural engineering have been solved using eigenfrequency optimization, such as maximizing the strength of RC column joints and vibration reduction in trusses. Additionally, this approach was used to optimize column dimensions using a surrogate membrane model of reinforced concrete moment frames, increasing the structure overstrength and ductility.

The performance of a building during an earthquake seems to be greatly affected by the smallest natural frequencies of the structure. The reliance of the seismic response on the natural frequencies has been leveraged to develop efficient structural analysis procedures for calculating the seismic response of buildings, such as the modal pushover analysis. Moreover, several standards use the dominating nature of the smallest natural frequencies to recommend seismic response methods such as the equivalent lateral force (ELF) and the modal response spectrum analysis, both using elastic models of the buildings.

The natural frequencies of a structure are properties that can be optimized using eigenfrequency optimization, suggesting that it is a suitable approach to design buildings with improved seismic performance. Furthermore, the optimization of the natural frequencies of a structure has low computational costs since the objective function uses the elastic model of the building to make the calculation, which is significantly less complex than the nonlinear analyses required by existing methods for optimizing the design of SMRF.

Challenges that face this method:

Developing an efficient formulation of eigenfrequency optimization for SMRF has three challenges. The first one is that the elements sections in a SMRF are represented by discrete variables, given by the typical steel section profiles used in construction practice. A second challenge stems from the fact that the problem optimizes natural frequencies; therefore, it is necessary to introduce a constraint to the problem that limits the cost of the building, ensuring a competitive design. A third challenge is ensuring that the resulting design satisfies design code requirements for resistance and functionality.

Solution:

Challenge1:

Handling this problem requires expressing the element sections of the SMRF as a vector of integer indexes, each one corresponding to a section profile, which has associated the corresponding section properties (area, moment of inertia, etc.)

Challenge 2:

This is addressed by imposing a limit W0 to the total weight of the building W(p), which is a function of the profiles p of the structural elements.

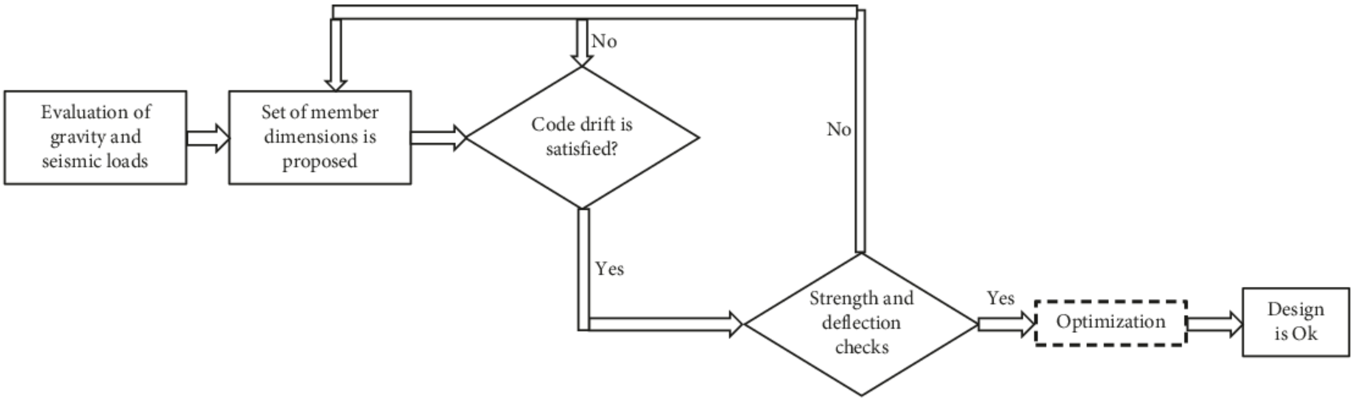
Challenge 3:

To overcome this challenge, each element of the building (i.e., columns and beams) must be limited between a minimum profile (Pi; min) and a maximum profile (Pi; max). In addition to fulfilling design code requirements, this scheme also contributes to limit the search space, avoiding the possibility of generating unviable solutions that would be discarded by the design code constraints.

With those considerations into account, the equation below shows the formulation of the eigenfrequency optimization problem for SMRF, based on the stiffness (*K*) and mass matrixes (*M*) of a given structure. Here Wn, is defined as the *n*-th natural frequency of the building and P is an integer vector with the section profiles, which has associated the corresponding section properties:

$$\begin{array}{ll} \max & \{\omega_n\}_{n=1,\dots,N,} \\ \text{subject to} & p_{i,\min} \leq p_i \leq p_{i,\max} \\ & W(\mathbf{p}) \leq W_0 \\ & \left[K - \omega_n^2 M\right] \varphi_n = 0. \end{array}$$

This formulation seeks to maximize the set of N first natural frequencies of the structure, subjected to three constraints. In the first constraint, Pi; min and Pi; max are the minimum and maximum index values of each element represented in P. The second constraint accounts for the volume limit previously discussed. The third constraint comes from the structural dynamic theory, and it means that Wn is a natural frequency of the structure.


Evaluation of gravity and seismic loads
Set of member dimensions is proposed
No
Code drift is satisfied?
No
Yes
Strength and deflection checks
Yes
Optimization
Design is Ok

Integration of Eigenfrequency Optimization in the Structural Design Workflow

Feasibility, understood as the degree to which the optimization procedure is easy or convenient to implement, is one critical aspect of an optimization method to succeed in engineering practice. As demonstrated in equation above, the proposed method uses the elastic properties of the building, so it is feasible for implementation in engineering practice.

Advantages of the method:

This approach has several advantages. First, the design that results from the optimization satisfies not only the strength requirements but also the drift limit, as the method is maximizing the fundamental frequency (i.e., minimizing the fundamental period) and the drift limit is checked in the elastic range. Consequently, optimized building will have a smaller one than the traditionally designed building. The second advantage is that unlike existing methods, the proposed method does not need to perform any nonlinear analyses, significantly improving the computational performance. A third advantage of the proposed method is that the proposed formulation works for any type of buildings, regardless of their irregularity and whether they are two-dimensional and three-dimensional problems. In the latter case, the stiffness matrix must be formulated using the frame-type element which has 6 degrees of freedom on each element end. Similarly, the mass matrix must account for the additional degrees of freedom. In all cases, the method requires that the strength and ductility requirements must be met by the proper selection of the Pi; min and Pi; max the for the members profiles.

Case Study:

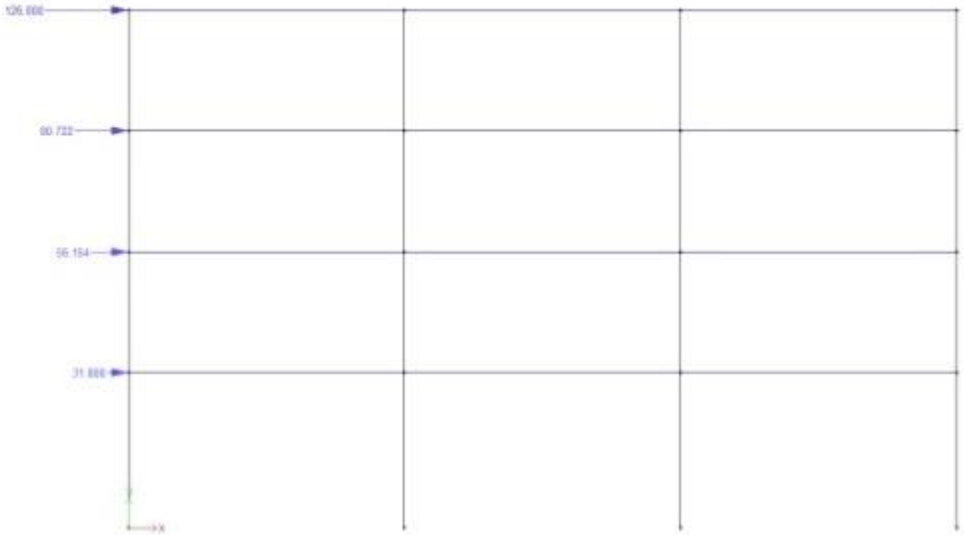
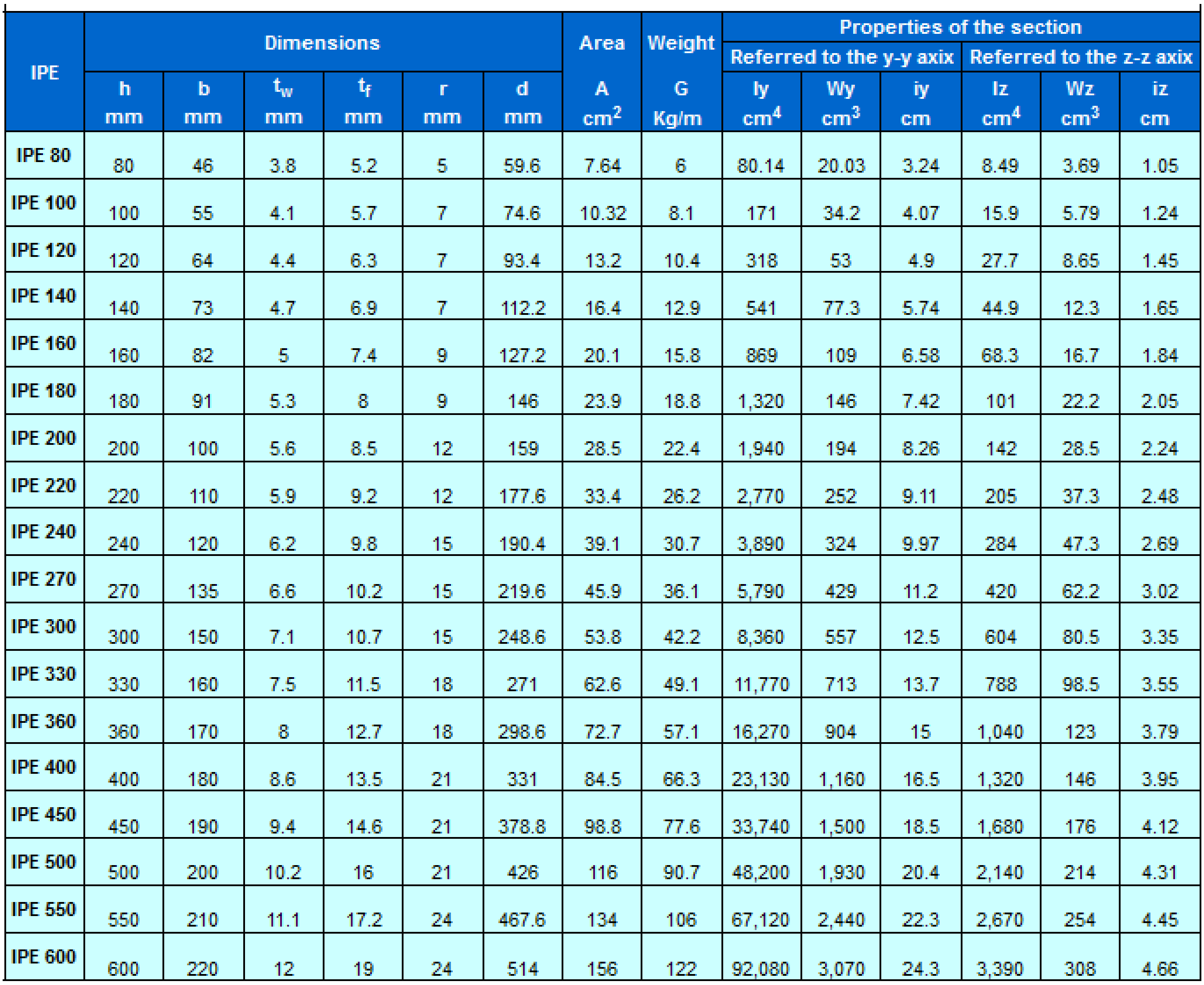


Figure 15 Earthquake actions (Transversal section)

Figure 1 :a four-story building with three identical beam spans of 6 m, and all the floors have a story height of 3 m.

This building was designed per the Load and Resistance Factor Design in the AISC 360-16 following the customary engineering practice. Our goal is to optimize the design of this structure following the method stated above.

Two section profile databases were used for this purpose. Tables 1 and 2 show the profiles used for beams and columns, which range from the IPE100 to the IPE600 and from HEA100 to HEA600, respectively.



IPE	Dimensions						Area	Weight	Properties of the section					
									Referred to the y-y axix			Referred to the z-z axix		
	h mm	b mm	t_w mm	t_f mm	r mm	d mm	A cm^2	G Kg/m	Iy cm^4	Wy cm^3	iy cm	Iz cm^4	Wz cm^3	iz cm
IPE 80	80	46	3.8	5.2	5	59.6	7.64	6	80.14	20.03	3.24	8.49	3.69	1.05
IPE 100	100	55	4.1	5.7	7	74.6	10.32	8.1	171	34.2	4.07	15.9	5.79	1.24
IPE 120	120	64	4.4	6.3	7	93.4	13.2	10.4	318	53	4.9	27.7	8.65	1.45
IPE 140	140	73	4.7	6.9	7	112.2	16.4	12.9	541	77.3	5.74	44.9	12.3	1.65
IPE 160	160	82	5	7.4	9	127.2	20.1	15.8	869	109	6.58	68.3	16.7	1.84
IPE 180	180	91	5.3	8	9	146	23.9	18.8	1,320	146	7.42	101	22.2	2.05
IPE 200	200	100	5.6	8.5	12	159	28.5	22.4	1,940	194	8.26	142	28.5	2.24
IPE 220	220	110	5.9	9.2	12	177.6	33.4	26.2	2,770	252	9.11	205	37.3	2.48
IPE 240	240	120	6.2	9.8	15	190.4	39.1	30.7	3,890	324	9.97	284	47.3	2.69
IPE 270	270	135	6.6	10.2	15	219.6	45.9	36.1	5,790	429	11.2	420	62.2	3.02
IPE 300	300	150	7.1	10.7	15	248.6	53.8	42.2	8,360	557	12.5	604	80.5	3.35
IPE 330	330	160	7.5	11.5	18	271	62.6	49.1	11,770	713	13.7	788	98.5	3.55
IPE 360	360	170	8	12.7	18	298.6	72.7	57.1	16,270	904	15	1,040	123	3.79
IPE 400	400	180	8.6	13.5	21	331	84.5	66.3	23,130	1,160	16.5	1,320	146	3.95
IPE 450	450	190	9.4	14.6	21	378.8	98.8	77.6	33,740	1,500	18.5	1,680	176	4.12
IPE 500	500	200	10.2	16	21	426	116	90.7	48,200	1,930	20.4	2,140	214	4.31
IPE 550	550	210	11.1	17.2	24	467.6	134	106	67,120	2,440	22.3	2,670	254	4.45
IPE 600	600	220	12	19	24	514	156	122	92,080	3,070	24.3	3,390	308	4.66

Figure 2': IPE100 to IPE600

Profile	ID	Area cm^2	Inertia (strong axis) cm^2		Profile	ID	Area cm^2	Inertia (strong axis) cm^2	Profile	ID	Area cm^2	Inertia (strong axis) cm^2
HEA100	1	21.2	349.2		**HEA280**	10	97.3	13669.9	**HEA600**	19	226.5	141199.9
HEA120	2	25.3	606.0		**HEA300**	11	112.5	18260.1				
HEA140	3	31.4	1033.1		**HEA320**	12	124.4	22930.2				
HEA160	4	38.8	1672.8		**HEA340**	13	133.5	27689.8				
HEA180	5	45.3	2509.9		**HEA360**	14	142.8	33090.0				
HEA200	6	53.8	3692.0		**HEA400**	15	159.0	45070.0				
HEA220	7	64.3	5410.2		**HEA450**	16	178.0	63720.0				
HEA240	8	76.8	7763.1		**HEA500**	17	197.5	86969.9				
HEA260	9	86.8	10449.9		**HEA550**	18	211.8	111900.1				

Figure 2'' : HEA100 to HEA600

The objective function and constraints were coded in MATLAB® and the multiobjective evolutionary algorithm, Borg-MOEA was used to solve the problem.

Results for the 4-Story Building:

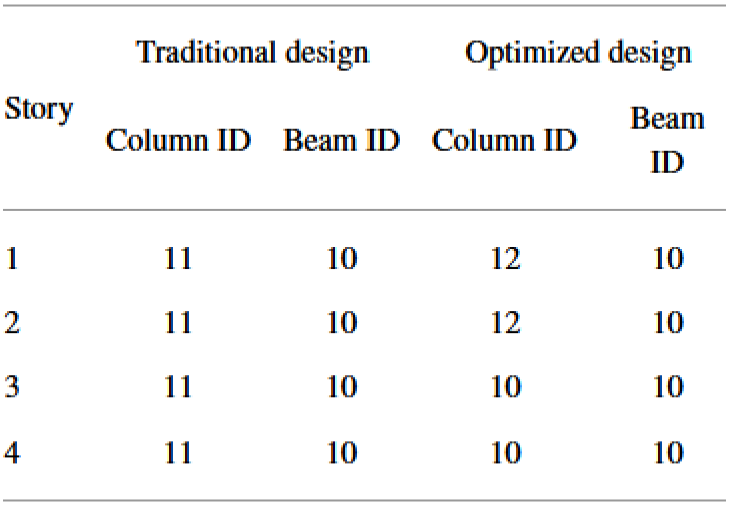
The proposed method is applied to a four-story building. This building is first designed according to the customary engineering practice for a base shear of 161.5 kN. The design results show that using profiles ID = 11 (HEA300) and ID = 10 (IPE100) for columns and beams satisfy all the drift, strength, and deflexion requirements. This design has a mass of 7.28 ton, which is used as W0 the limit for the problem formulation. Since this is a low-rise building, the fundamental frequency was considered as the only objective function.

A key step to the optimization of this structure is choosing suitable values for Pi; min and Pi; max and defining the first constraint.

Pi; min: a good strategy for beams is selecting the smallest profile that satisfies the serviceability (deflexion) requirements of the design code. One way to conduct this task is analysing the floor system for the gravity loads and finding the profile for which the deflexions are closest to the code limit for the building. For this structure, beam ID = 9 (IPE270) satisfies the strength and deflexion requirements; hence, they are used as the Pi; min.

We should note that Pi; min should be selected simultaneously with Pi; max, and for this case column ID = 10 (HEA280) and beam ID = 11 (IPE330) are selected for the columns Pi; min and beams Pi; max.

The table below shows the results of the building design by the traditional method and the optimizing method:



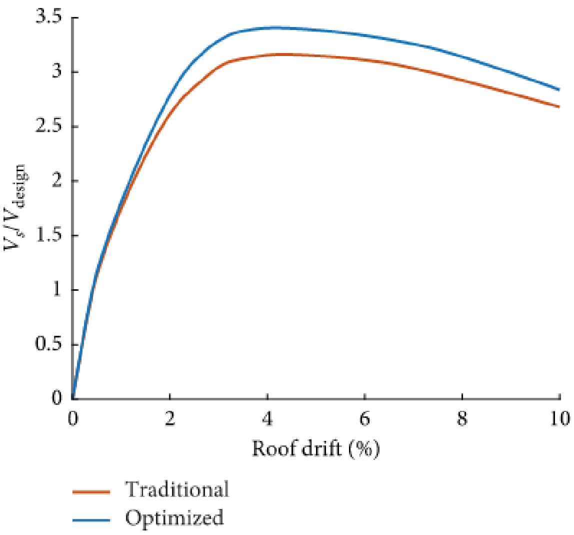
Story	Traditional design		Optimized design	
	Column ID	Beam ID	Column ID	Beam ID
1	11	10	12	10
2	11	10	12	10
3	11	10	10	10
4	11	10	10	10

Conclusions:

This table shows that the proposed method did not change the building's beam configuration, leaving all floors with the initial ID = 10 (IPE300) profile. This result may stem from the additional constraint imposed to the objective function that beams within a same floor must use the same section profile. This constraint was included to accommodate construction practices, where it is common for all beams within a same floor to use the same section. Regarding columns, the method assigns ID = 12 (HEA320) sections to columns of the first two stories and ID = 10 (HEA280) to columns in the top half of the building. The material consumption for this building is 7.22 ton, a 0.8% reduction compared to the traditional alternative. In terms of ratio of the column inertia to beam inertia, column ID = 12 to beam ID = 10 in the first two floors of the optimized design is 2.74, a 25% increase compared to the 2.18 in the traditional design. On the other hand, for floors 3 and 4, this ratio decreases to 1.63. In all cases, these ratios satisfy the code constraints.

Seismic performance of the building:

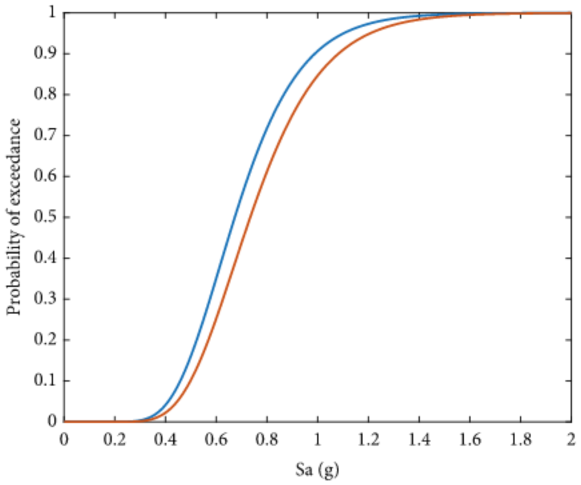
The results for the traditionally designed building and the building designed per the proposed method are shown in the picture below. The *X*-axis shows the roof drift ratio (RDR) of the buildings as percent, and the *Y*-axis shows the ratio (*Vs/Vdesign*) between the base shear *Vs* in the pushover and the design base shear *Vdesign* of the building.



The results from this analysis show that the buildings have almost identical performance up to 1.5% roof drift, suggesting that the seismic performance for small earthquakes will be similar.

After this point, the building designed per this method shows better performance, exhibiting a higher overstrength.

Compared to the traditionally designed building, the seismic performance at the life safety and collapse levels for the building designed following the procedure presented is improved. These benefits come without any additional costs in materials and were achieved after less than 30 minutes of computational time.



General conclusion :

Compared to existing alternatives, this method based on eigenfrequency optimization has the advantages of being computationally efficient and feasible to implement. These benefits stem from the fact that the method uses the information of elastic models of the buildings.

This method produces designs of steel moment frames that have superior seismic performance than buildings designed following the customary engineering practice. The results from the seismic performance for a four-story building show that the building designed using the proposed method is 12% less susceptible to collapse than its traditionally designed counterpart. Eigenfrequency optimization is a viable framework to optimize the design of steel moment frames, which lends itself to be implemented and solved using evolutionary approaches like genetic algorithms. The method can be used for buildings with more complex dynamic responses as it allows incorporation of more than one natural frequency as objective function.

Perspectives of expanding the subject:

Moroccan statistics and new projects in the design office:

The seismic activity in Morocco is not as important as in other world areas such as Japan, California, Greece, Turkey, etc. Nevertheless, background seismicity in Morocco is not negligible and has produced a few historical and instrumental earthquakes with local magnitudes above 6. The Agadir earthquake 1960, for instance, destroyed this city with several villages and caused 12,000 deaths. Later, other remarkable earthquakes occurred: in Al Hoceima in 2004 in the North of Morocco, caused 629 deaths. However, seismic risk is relatively high due to vulnerable buildings that are either old or don't respect seismic standards. One of the earliest projects regarding earthquake proofing buildings in morocco date back to 1960 after the deadly earthquake in Agadir and it was called "building a new resistant city"; A High Commission for Reconstruction was established and special earthquake resistant methods were officially approved. No building permission is given if even the smallest construction does not conform to the "Norms Agadir 1960." These norms define all construction requirements and stress the importance of avoiding unsafe building sites such as steep slopes, water- impregnated ground, sandy soil or rubble filled soil. Rocky ground is considered best. The specifications call for horizontal foundations but if the foundation is built on two levels, the joints should be reinforced. There must be steel wire fabric reinforcement at ground level. Joints must also be provided be-tween the two sections of a building for they will react differently to seismic vibrations. Even the type and quality of building materials such as sand, bricks, steel, cement and water used in mixing concrete are defined.

Since the concept isn't new but certainly needs improvements, the Eigenfrequency optimization is the perfect way to both optimize the weight and the cost of future seismic designs. We can start by proofing small portions of zones of the highest risks and this means **Seismic** retrofitting old houses and optimizing their weights while taking in consideration forces of stress, constraints and side to side forces.

Future research on this topic can be pursued in several topics. One interesting area is evaluating the benefits of the proposed method for other building configurations, particularly for high-rise buildings where several frequencies are needed to capture the dynamic response and which would be required as objective functions. Considering the potential to be a computationally efficient method, it is a worthy topic to investigate the method application to optimize three-dimensional buildings with different types of irregularities.

Conclusion:

This study employs an organized methodology for finding the optimum shape of the structures under earthquake loading. The numerical examples show that the optimum shapes are obtained in a few iterations. Furthermore, it could be applied easily with small modifications to three-dimensional structures. To finish this research, I would like to add that this is not the only method available to optimize the shape of the structure under earthquake or generally speaking dynamic loads. As mentioned before, there are many ways to build a resistant structure and therefore there are many algorithms to do so. I would like to mention the method of the finite element analysis where earthquake loading is transformed into the equivalent static loads (ESLs) and the stresses are computed from the differentiations of the displacement field.

As technology goes further, we may be able to create different and more efficient ways to optimize our structure and probably even predict the time of the occurrence of an earthquake leading to the creation of better shields that protect future generations from our furious earth.

References:

https://www.semanticscholar.org/paper/A-Method-to-Improve-the-Seismic-Performance-of-on-Arroyo-Osorio/3e364453a1aaa1a3a5d7c2f399c7ca9df71127f9

https://www.nytimes.com/interactive/2019/06/03/us/earthquake-preparedness-usa-japan.html

http://eqseis.geosc.psu.edu/cammon/HTML/Classes/IntroQuakes/Notes/earthquake_effects.html

https://link.springer.com/article/10.1007/s00158-012-0864-7

https://journals.sagepub.com/doi/abs/10.1177/1369433219878856

https://www.iitk.ac.in/nicee/wcee/article/13_1060.pdf

http://www.staticstools.eu/en/profile-ipe/ipe100/mm

https://eurocodeapplied.com/design/en1993/ipe-hea-heb-hem-design-properties

https://www.aisc.org/globalassets/aisc/awards/tr-higgins/past-winners/load-and-resistance-factor-design.pdf

https://www.bigrentz.com/blog/earthquake-proof-buildings

https://www.prontubeam.com/structural-steelwork-handbook

https://www.wizdom.ai/publication/10.1016/S0045-7825(00)00284-X/title/eigenfrequency_optimization_in_optimal_design

http://www.cmapx.polytechnique.fr/~allaire/allaire-aubry-jouve.pdf